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A Detailed Optimisation of Solar Photovoltaic/Thermal Systems and its Application.

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Abstract

There have been various studies and experimental results analysing the operational behaviour of PVT, most of which has been done at steady state or quasi-state. Variable factors can be controlled to optimise the PVT output such as mass flow rate, irradiation falling on the PVT through tracking or incidence angles in a day and fixed factors that depend on the design of the chosen PVT system as well as location parameters such as ambient temperature, wind speed, Transport Fluid used, Difference in Structure, Packing Density, Nominal operating temperature, stagnation temperatures, Fill Factor, Thickness of each layer, Location and Latitude and Heat removal factor (harp or serpentine design). The aim of this research is to validate and predict the dynamic behaviour of PVT systems while accurately describing the factor responsible for the loss of efficiency at any point in time under various weather constraints. A commercial system was considered (Solar Angel PVT system) here and is simulated for an entire year. The system was modelled in MATLAB and solved in implicit RK-4 method. The research question finds out to establish the basis for a standard testing protocol for assessing PV-T performance throughout various differences. It also analyses the long-term dynamic performance of PV/T technology by providing evidential data analysis (solar irradiance, heat and electricity, ambient temperature, operational temperatures, flow rates and thermal storage capacity) while completing an assessment of PVT behaviour with respect to an equivalent PV under different weather conditions. The flow rates, heat removal factor and the location affect the thermal behaviour of the PV/T to a greater extent than nominal temperatures and stagnation temperatures.

Keywords: Solar Energy;Dynamic Modelling;Optimising;Electric and Thermal Energy; Solar Photovoltaic thermal systems;PVT systems with storage;Optimal operation of PVT.

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1. Introduction

Among all renewables sources, solar energy is considered as one of the leading and trending resources because of attractive features like being environment friendly, having zero-emissions, easy integration and shorter payback periods each year with easier accessibility and abundance of energy. There are two types of solar energy one being classified as Photo-Voltaic (PV) energy generated as electricity from short wave solar radiation and the other as thermal energy generated heat from long wave solar radiation. Solar PV cells only convert around 10-20% of incoming solar radiation to electricity and the remaining energy is dissipated as heat or lost to surroundings. But from previous studies, PV cells show a decline in performance with an increase in temperature. This can be rectified by removing the excess heat generated at the PV panels. The concept idea of PV/T systems was first presented by stratifying and modifying the Hottel-Whillier-Bliss equations for solar collectors suitably for PV/T systems in the mid-1970. Since then, there has been a large surge of studies during the following decades. Majority of the studies analysed the performance of the PV/T by modelling and experimental analysis under various changing constraints like mass flow rate, ambient temperature, wind speed, solar irradiation either in steady or quasi state. The primary concern in PV/T systems is to improve the electric efficiency of PV cells by extraction of excess heat and the secondary priority is to utilise the heat generated. In an analysis conducted by Vokas et al showed a theoretical performance at steady state for different locations at different tilt angles and conveyed that the cooling and heating load is greatly affected by location [21]. In another study by Dubey S et al, among four case studies of different cross-sections of PV and Glass relation, Glass to Glass PV modules seem to generate more electric efficiency and higher air temperature. The key parameter that was focused by Guarracino et al was the number of covers where electric efficiency was highest for unglazed and thermal efficiency was highest for double glazed higher emissivity can adversely affect thermal output by 10% [7]. Sun et al investigated the effects of tilt angle and connection modes of PVT either in parallel or series and reports that optimum tilt angles are chosen closer to the latitude and in locations with lower latitudes, the tilt angle needs to be higher to increase projection, it was also found that series connections lower electric efficiency due to higher heat gain when compared to a parallel connection mode [20].

Nomenclature

c	convection transfer
r	radiation transfer
h	heat-transfer coefficient (W/m^2K)
M	Mass of the object (Kg)
a	Ambient conditions
A	Area of radiation incident on glass (m^2)
Ac	Area of the Solar cell
b	Absorber node
u	weld bond node
p	PV node
i	Insulation node
f	fluid node
g	Glass node
T	Temperature of respective node (K)
t	time
τα	transmission absorptance product
w	wind velocity (m/s)
Ul	total heat loss coefficient (W/m^2K)
W	spacing distance between tubes (m)
D	Diameter of tube (m)
C	heat capacity (J/Kg/K)
m	mass flow rate (Kg/sec)
FR	heat removal factor

Qheat	Useful heat gain (W)
Gs	Absorbed Radiation (W/m^2)
Tin	Inlet Temperature
Cp	Fluid heat Capacity
Tout	Outlet Fluid Temperature

1.1. PV/T Panels

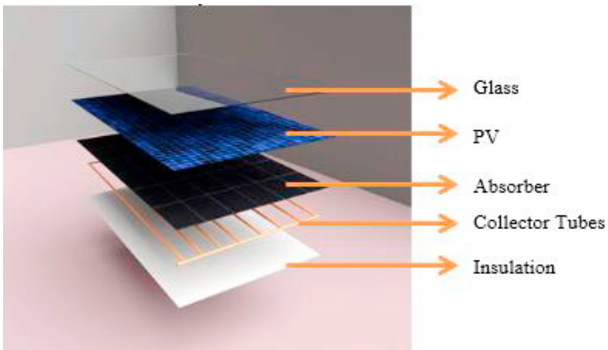

Fig 1.Isometric 3D view of Modelled PVT

The PV/T model considered here is a commercial model (Solar-angel DG-01) that has the low iron glass for absorbing maximum short-wave radiation and reduce heat losses, PV panel and the aluminum absorber plate held together by EVA (Ethyl vinyl acetate) layers by thermal bonding with no air gap. The tubing for the thermal collector part is made of aluminum and the final layer is a polyurethane foam of insulation to prevent any heat losses. According to the DoBEaIS [5], the above PV/T is classified as type 2, which is one of the common commercial product configurations in the UK. The type 2 PV/T has different thermal behavior at different locations and this need to be validated.

Solar electric efficiency of PV/T systems has shown an improvement of 4-12% when controlled using appropriate parameters, while comparing with a Solar PV only and can generate a thermal efficiency of 60-70% [1][2][18][17]. But there will always be system tradeoff between electric and thermal efficiency and the output needs to carefully chosen. As PV/T's do not generate enough heat all year round especially for the winter months, it is common practice to combine with an auxiliary heating source to compensate. To understand and compare behavior of different PV/T systems there needs to be standard. However, the EU/British /international standards for PV/T systems have not yet been established quite fundamentally and this project will be a foot forward in that direction. The lack of standard was attributed to not having enough studies that consider all the factors and the percentage effect of those parameters on the output [5].

1.2. Case studies

To find the performance of PV/T systems, there are some performance indicators that were defined over the years. They can be assessed by finding the electricity generated, heat generated, useful heat transfer, flow in and flow out temperatures, storage tank temperature, solar input irradiance and solar panel temperature at the location. There were no studies that had all the aggregated data automatically collected and hence no conclusive results were obtained. Those few studies that could generate a general understanding of monthly results and system size and variations were also among some limitations. Hence a comparison would not draw enough data. Through this project, attempts to correlate all the parameters were considered and enough data was collected for an unbiased comparison and analysis. A 2.5KW PV/T system with 20° tilt angle and fixed flow rate system was considered for validation with an actual system installed at Newcastle University,UK. A system of 12 PV/T's that generates heat and of which only 10 panels were used to generate electricity is utilised here. A differential controller controls the pump when there is a differential temperature between the solar panel and the heat exchanger located at the output of the PV/T. The heat transfer fluid used here has a 20% glycol-water mix which affects the fluid capacity of the system. This is due to the freezing temperature during winter season.

2. Modelling and Methodology

The PV/T system is inherently dynamic as its input is not steady and steady state analysis will not be sufficient for a rigorous study of thermal behavior and for controlling the system according to the parameters. Hence, we consider a dynamic modelling using explicit analysis/implicit analysis of the entire system with the corresponding energy and exergy analysis. Explicit analysis of the system maybe unstable if the stability condition is not met [3]. Implicit analysis gives a more accurate representation the system but it is slightly complex than explicit analysis. An implicit analysis and RK-4 method is used to solve the system to compare the solution for a more accurate measure.

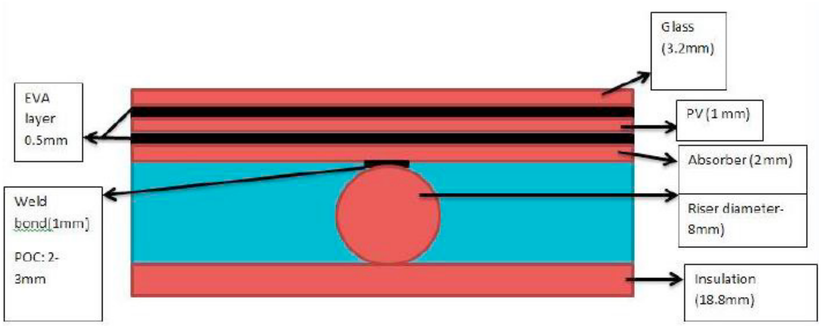

Fig 2. Cross-section of the PV/T

This section presents a mathematical model describing the flat-plate solar collector system considering the transient properties of its different zones. In the proposed model, the analysed control volume of the flat-plate solar collector contains the cross section that is divided into six nodes. Energy balances at these six nodes are considered. The energy balance caused by the mass transfer during the circulating of the fluid within the solar collector is included by the definition that the collector's temperature depends on the coordinate in the direction of the fluid flow. Taking N nodes in the flow direction means that the model describes (6 x N) nodes. The governing equations were derived by applying the general energy balance for each zone in the analysed control volume of the solar collector. For one-dimensional heat transfer, the general energy balance principle is given by the change in internal energy is equivalent to the heat generated and the difference of heat transfer rates in the system [3]. They are obtained as follows from the six equations as shown below.

$$MgCg\frac{dTg}{dt} = (hacA + harA)(Ta - Tg) + Wg + hcgA(Tp - Tg)$$

$$MpCp\frac{dTp}{dt} = hcgA(Tg - Tp) + hbpAbp(Tb - Tp) + hpuApu(Tu - Tp) + Wp$$

$$MbCb\frac{dTb}{dt} = hbpAbp(Tp - Tb) + hbuAbu(Tu - Tb) + hbiAbi(Ti - Tb)$$

$$MuCu\frac{dTu}{dt} = hbuAbu(Tb - Tu) + hiuAiu(Ti - Tu) + hufAuf(Tf - Tu) + hpuApu(Tp - Tu)$$

$$MiCi\frac{dTi}{dt} = hbiAbi(Tb - Ti) + hiuAiu(Tu - Ti) + haiA(Ta - Ti)$$

$$MfCf\frac{dTf}{dt} = Aufhuf(Tu - Tf) - mfCf(Tin - Tout)$$

$$F' = \frac{1}{\frac{WUl}{\pi Dhuf} + \frac{1}{\frac{D}{W} + \frac{1}{\frac{WUl}{Cu} + \frac{W}{(W-D)F}}}}$$

$$F'' = \frac{mCp}{AcUlF'}[1 - \exp(-\frac{mCp}{AcUlF'})]$$

$$F = \frac{\mathrm{Tanh}\, Mh(W-D)/2}{Mh(W-D)/2}$$

$$FR = F'F''$$

$$(Atnoload)Ul = \frac{TpNOCT - TaNOCT}{GNOCT(\tau\alpha)}$$

$$Qheat = AcFR[Gs - (Ul(Tin - Ta)]$$

$$Packingfactor\,\beta c = \frac{areaofsolarcells}{areaofPVModule}$$

Each of these balance node equations defines a heat transfer coefficient between each layer where the heat transfer interacts from Duffie and Beckman[6]. Using laws of Convection, radiation and Conduction at these nodes, the heat transfer coefficients are defined and calculated. All the terms have been described in the Nomenclature.

2.1. Calculation method:

Energy balance at each node by using ray trace method is calculated and solved in RK-4 implicit method and the set of ODEs are solved iteratively to find temperature at each node, a separate PV analysis is also done to reveal the Electric output during the simulation. The parameters like Mass flow rate, Nominal operating cell temperature (NOCT), solar radiation, wind velocity, ambient temperature, incidence angle (that changes over location) and tilt angles are varied are observations are made. Fixed parameters like the Stagnation temperature, packing density are decided by the manufacturer. Stagnation temperature is the maximum temperature reached when the fluid is not distributed through the closed loop. At such a condition, the useful thermal gain and efficiency is zero, meaning all the absorbed radiation is lost as thermal losses. The stagnation temperature depends on the manufacturer and the PV/T panel use. For this project, the stagnation temperature is rated at 79°C**.**The heat removal factor is dependent on the geometry, the fluid capacity of the system, mass flow rate and the heat transfer coefficients and the useful heat gain is directly proportional to the heat removal factor (FR) as described by the equations shown above.

3. Results and Discussion

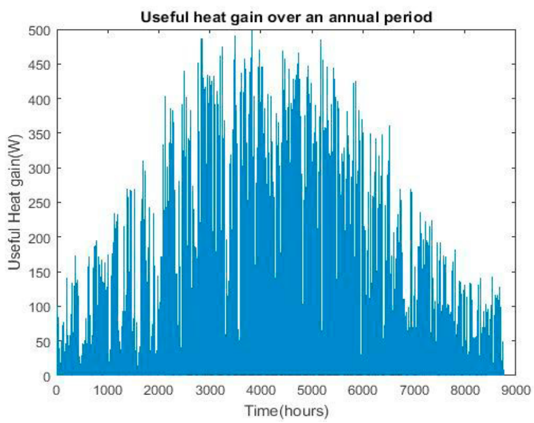

Fig 3 Useful heat gain over an annual period

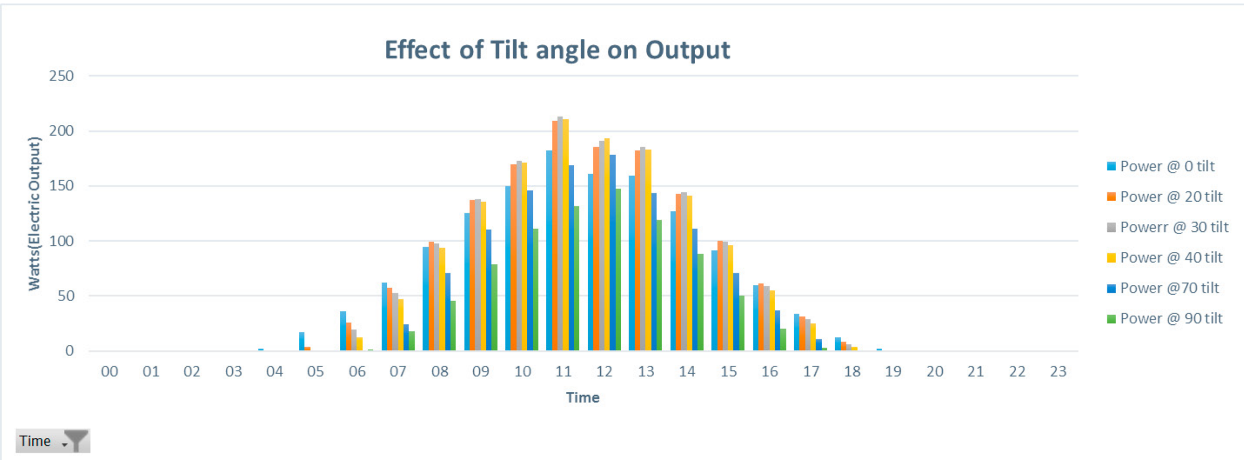

Fig 4 Effect of Tilt angles on electric output in a day

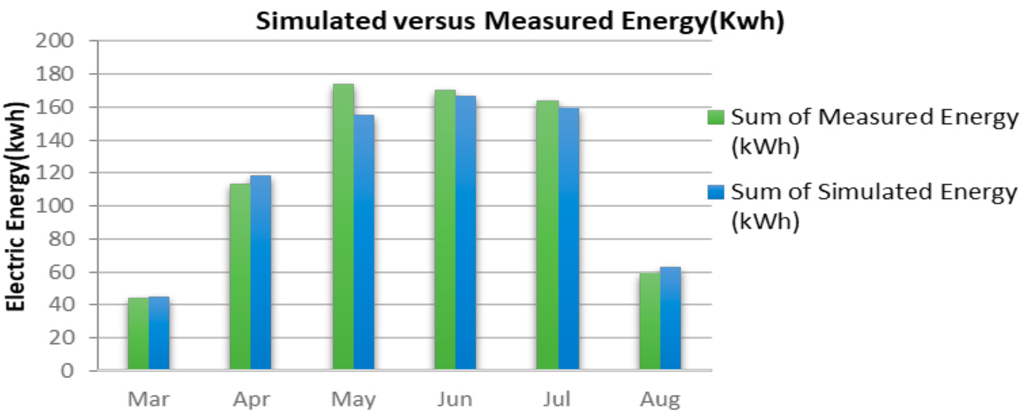

Fig 5 Measured and Simulated Energy of PV/T's of case study at Newcastle over 6 months

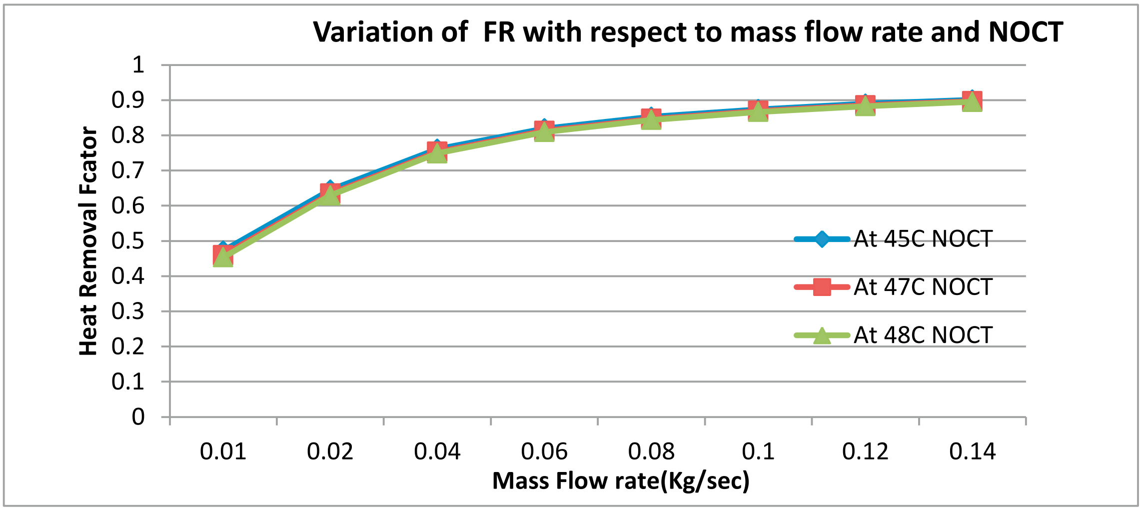

Fig 6 Variation of FR with respect to mass flow rate and NOCT

In Fig 4. A validation was drawn between actual and simulated energy and an error of around 4.2 % was observed. The real time system installed has had some delays in the installation and data collection process. The Solar angel is rated at 250Wp electric output and 648Wp heat output. Through simulations, we obtain the annual heat output that can be observed as 500Wp generated in summer shown in figure 3. Figure 6 shows an effective variation on heat removal factor due to NOCT. It can be observed that the mass flow rate has a significant effect on the heat removal factor with respect to NOCT. This indicates that higher mass flow rate improves the heat removal factor and as the useful gain is directly proportional to the heat removal factor, output is thus affected by mass flow rate. Care has to be still taken when designing the system with higher mass flow rates to avoid pump losses. The optimum tilt angles as said by Duffie and Beckman and can be varied from latitude of location±10º depending on the whether to track output at winter or summer [6]. According to figure 4, the optimum tilt angles for UK range from 20º to 40º, with the optimum being 30º. The fluid heat capacity Cp depends on the location selected (mixed with percentage of ethyl glycol) and should exponentially affect the heat output.

In order to apply the model and design a system, a 4 bed house case is selected for Newcastle based on the results obtained. The electric demand and heat demand can be supplied by an appropriate design, cost and area available.

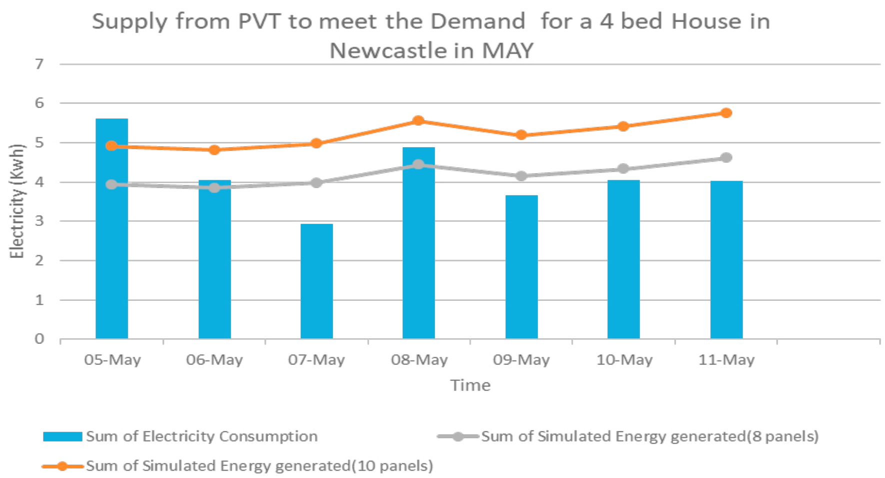

Fig7. Electric demand and Supply in summer week.

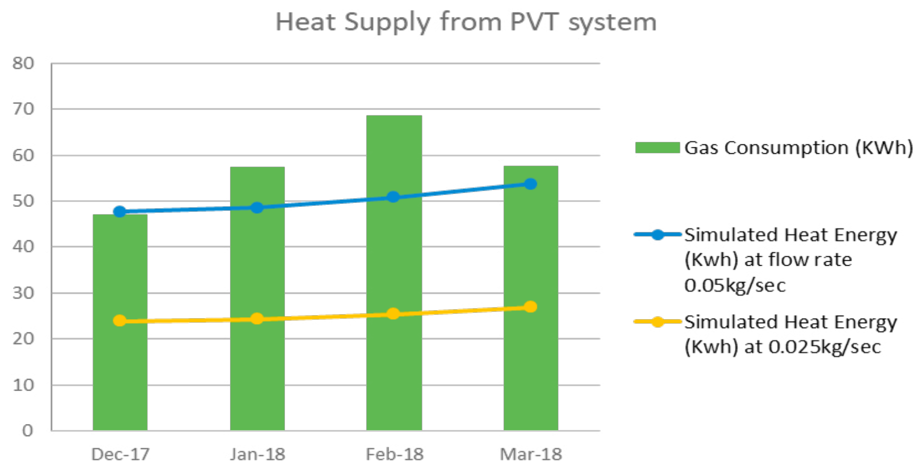

Fig 8: Heat demand and supply in winter months

When the actual data can be predicted along with having an understanding of the controlling factors, it can give us a broader understanding of the system as a whole. In fig 7, the excess electric energy can be stored and used when there is deficit energy.

4. Conclusion

We can obtain higher heat gain output from the panels if the mass flow rate is increased, the output from one module can be matched with the maximum thermal output of the system. This is one of the factors used for controlling the output temperatures.

The model has seen an increase in heat gain during the summer months. The electric gain varies when tilt angles are varied and a higher thermal output is produced when the mass flow rate is increased from the initial constant value of 0.01kg/s to 0.14kg/s as the thermal output is directly proportional the heat removal factor. A comparison between simulated and available actual Electricity energy data suggest that there is a variation in energy generated caused due to weather data error and fixed mass flow rate (0.04kg/sec). It was observed that flow rates, heat removal factor, tilt angles, latitude and longitude as well as the fluid used to remove heat affect the system more than other factors like NOCT, packing density and stagnation temperature which are more or less fixed. As the system is a commercial product, optimising an existing system, improving the efficiency and standardising the testing performance is promising for any future stakeholders.

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